Narrow Bandgap Intersubband Thermophotovoltaic Cells

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***Abstract* — Narrow bandgap thermophotovoltaic cells are needed to reach high power density with low temperature sources. However, bulk junction narrow gap cells face challenges including high nonradiative losses, challenging epitaxial growth, and high-cost substrates. An alternative approach is to use quantum-engineered structures comprised of wider bandgap materials to obtain low effective bandgaps. Here, we describe one such device, an intersubband photovoltaic cell, which operates similarly to a quantum cascade photodetector. We experimentally measured power generation from a quantum cascade cell illuminated by a thermal source, and we performed optoelectronic simulations to identify strategies for improved cell performance.**

I. Introduction

Many proposed applications for thermophotovoltaic (TPV) converters only offer source temperatures well below 1,000 °C, which motivates the use of narrow bandgap photovoltaic (PV) cells to obtain reasonable power density. Unfortunately, the performance of bulk junction narrow gap PV cells significantly lags their higher bandgap counterparts [1] due to difficulties in mitigating nonradiative losses. Additionally, narrow gap materials can be more difficult to grow by metalorganic chemical vapor deposition (MOCVD) as they typically require precursor gasses to pyrolyze at lower growth temperatures.

This has led researchers to examine more exotic structures based on quantum cascade lasers and photodetectors, which include interband cascade and intersubband cascade devices [2,3]. Interband cascade PV cells leverage interband transitions between valence and conductions minibands, while intersubband cascade PV (ISPV) cells utilize transitions between conduction subbands. Interband cascade PV cells have received considerable experimental attention [4], but ISPV cells have only been examined analytically by a few authors.

Because ISPV cells use transitions between conduction subbands, they are unipolar, majority carrier devices with small effective bandgaps defined entirely by wider bandgap materials. This means they can be grown on more readily available GaAs or InP substrates, their growth is facilitated by the use of wider bandgap materials, they are self-passivating, and they are insensitive to material defects because the activation energy of trap states is large compared to the intersubband gaps.

To begin to explore the potential of these devices, we performed transport modeling to design an initial ISPV cell, finite element electromagnetic modeling to examine light-coupling methods, and experimental measurements of a quantum cascade device under thermal illumination. Our results suggest that IPV cells have potential to be significantly improved and compete with bulk junction cell performance.

II. Results and Discussion

We grew an intersubband quantum cascade laser (QCL) by MOCVD to test in a power generation configuration, even though this particular structure is not optimized for PV operation. Deep-etched (~20 µm wide x 3mm long) ridge waveguide QCLs were fabricated, which consists of 40 stages of digitally graded GaInAs/AlInAs quantum wells and barriers, and it has an emission/absorption peak at about 4.6 µm [5]. We exposed the QCL to an electrically-driven thermal IR source as illustrated in Fig. 1(a), which has a peak intensity near 3 µm, and this light was collimated and then focused onto the edge of the QCL. Current-voltage (IV) scans were taken of the QCL for varying powers supplied to the IR source. The resulting current-voltage characteristics of the QCL are shown in Fig. 1(b). The QCL rapidly heats up to an elevated steady-state temperature under illumination, which causes the change in slope of the IV trace near the origin. As the illumination intensity is increased, we observe a clear photocurrent associated with the negative y-intercept and increasing power generation associated with the

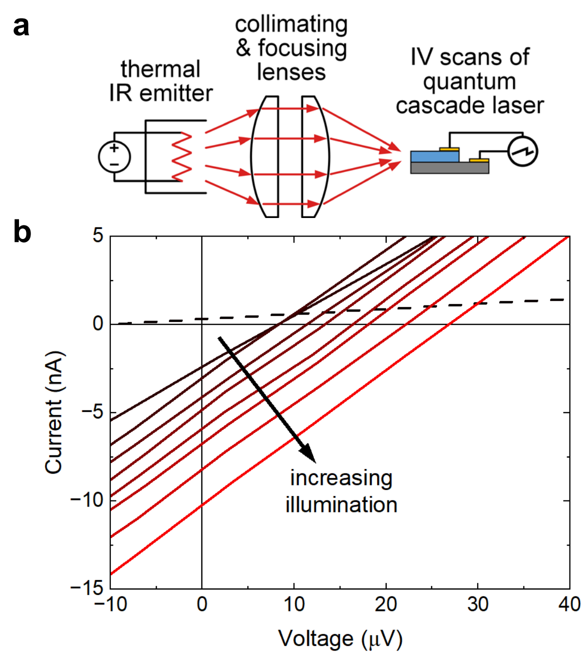

Figure 1. (a) Schematic of the measurement setup and (b) measured current-voltage characteristics in dark conditions (dashed line) and under illumination from a thermal emitter.

IV curve in the fourth quadrant. Even though the voltages, currents, and powers are quite small, to the best of our knowledge this experiment is the first demonstration of power generation with an ISPV cell from a thermal source, and it provides critical evidence that these devices can indeed be used as TPV cells.

We also performed quantum optoelectronic simulations of several different types of structures. These included a quantum cascade laser (QCL) similar to that tested, a modern intersubband QCD designed for operation at 4.3 μm [6], and an improved ISPV design that we developed with some limited optimization. Current-voltage characteristics assuming a 1 μm thick active region are shown in Fig. 3(a). Band structures for a single stage at the maximum power point for the QCD and ISPV devices are shown in Figs. 3(b) and (c), respectively. The QCL structure achieves a relatively low photocurrent as expected, because the optical wells are undoped and not designed for absorption. The QCD shows a much higher photocurrent at low voltages, but it is not intended for power production and the voltage falls off quickly with forward bias. The new ISPV design, on the other hand, exhibits a relatively flat current at zero bias and a much higher fill factor and open-circuit voltage compared to the QCD. By comparing the band structures of the QCD and ISPV devices in Fig. 3(b) and 3(c), we see that the ISPV cell has much fewer wells and barriers in a single stage (allowing for more stages), higher barriers next to the optical well (reducing thermionic emission), and slightly tapered wells and barriers. Finally, there is reduced overlap between adjacent coupled states in the cascade region. Although more study is required to fully understand why each of these effects leads to the substantial power generation improvement compared to a traditional QCD structure, there is clearly potential to design these to operate with substantial power generation.

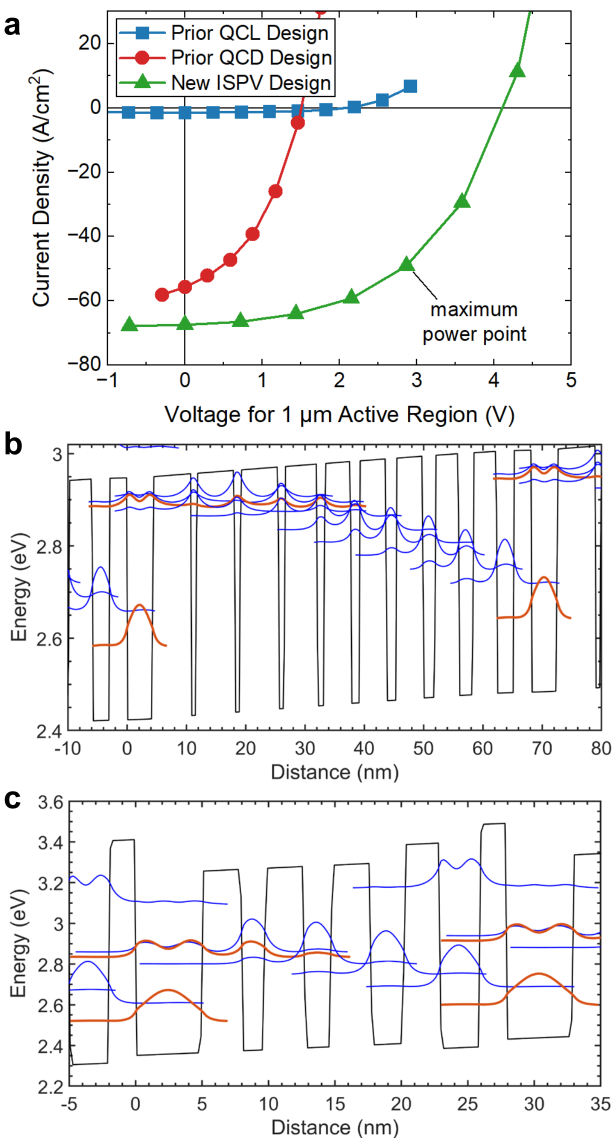

Figure 2. (a) Simulated current-voltage characteristics under illumination for a QCL, QCD, and our ISPV design, all assuming a 1 μm thick active region. The band structures for the QCD and ISPV devices are shown in (b) and (c), respectively.

III. Conclusions

Our results suggest that intersubband quantum cascade devices can be designed to produce power when operated in a photovoltaic configuration. The optimum structure for this is substantially different than a traditional QCD. Additional simulations of electromagnetic coupling, not provided here, indicate that structures can be fabricated to effectively couple light into the active region and meet polarization selection criteria. Future research will elucidate the underlying behavior and demonstrate high-performance ISPV cells.

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